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Studies of Quarkonia Production with CDF

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ABSTRACT

In this paper we present results on quarkonia production obtained from data taken with the CDF detector at Fermilab, in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

1 Introduction

We report on a study of J/ψ , $\psi(2S)$, χ_c and Υ production at the Tevatron. This study is interesting both by itself and for its contribution to the understanding of b -quark production. It yields the P_T dependence of the production cross section times the corresponding branching fractions of the above states to final states containing two muons.

Our data have been taken with the CDF detector¹ during the 1988-89 and the 1992-93 collider runs. The CDF detector has been upgraded before the start of the 1992-93 run. The upgrades relevant to this presentation are the muon chamber upgrade and the employment of a silicon vertex detector (SVX). The original CDF Central Muon detector, which covers the pseudorapidity region $|\eta| < 0.6$, has been complemented by the addition of four layers of drift tubes behind 2 feet of steel. As a result, hadronic punch-through backgrounds to the muon signal have been reduced by a factor of ~ 10 . We have also added layers of drift tubes in the pseudorapidity region of $0.6 < |\eta| < 1.0$ in order to increase our muon coverage. Finally two barrels of four layers of DC coupled, single sided, silicon detectors (SVX) with R- ϕ readout have been added around the beam-pipe. The four layers are arranged between $r = 3$ to $r = 8$ cm from the beam line, and the barrels cover the region $|z| < 26$ cm. The SVX provides a very good resolution in the transverse position of primary and secondary vertices. The primary vertex resolution in a typical event is $35 \mu\text{m}$, similar to the transverse beam size. The impact parameter resolution is better than $40(15) \mu\text{m}$ for tracks with $P_T > 1(10) \text{ GeV}/c$. We have collected $\sim 21 \text{ pb}^{-1}$ of data with this upgraded detector during the 1992-93 run.

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2 Quarkonia production

2.1 1988-89 data

In the 1988-89 collider run we studied the reactions $p\bar{p} \rightarrow J/\psi(\psi(2S))X \rightarrow \mu^+\mu^-X$ by using $2.6 \pm 0.2 \text{ pb}^{-1}$ of data. This allowed us to shed some light on the quarkonia production mechanisms at the Tevatron energy. The production mechanisms of the J/ψ 's($\psi(2S)$'s) are B decays, direct charmonium production and the recently suggested² gluon fragmentation. We obtained the J/ψ and $\psi(2S)$ differential cross sections which are displayed in Fig. 1 as functions of P_T . The number of J/ψ and $\psi(2S)$ events used in the measurement of those cross sections was 889 ± 30 and 35 ± 8 respectively. Theoretical predictions for the two types of processes expected to dominate J/ψ and $\psi(2S)$ production are also plotted. The solid curve in Fig. 1a (1b) is a next-to-leading-order (NLO) calculation of the production of b -quarks by Nason, Dawson, & Ellis (NDE)³ leading to B-mesons and subsequent decay to J/ψ ($\psi(2S)$) as discussed in Ref. 4. We refer to this overall calculation as B-production model (BPM). The dashed curve in Fig. 1a (1b) corresponds to J/ψ 's ($\psi(2S)$'s) from direct charmonium production⁵, that is, either from the decay of a higher charmonium state or from direct production through gluon fusion. We refer to this overall calculation as the charmonium production model (CPM). The sum of these two contributions (BPM and CPM) is also plotted in Fig. 1. The data show a production rate larger than expected. In Fig. 1a we fit the theory to the data by summing the two theoretical contributions with independent normalization factors. With no normalization constraints a good fit is obtained with $\sim 69\%$ J/ψ production from CPM and $\sim 31\%$ J/ψ production from BPM. Using additional information which is described in Ref. 4, we found that the 90% C.L. upper limit on the BPM contribution is $\sim 60\%$; we concluded as well that if future measurements exceed this value, then either at least one of the two models considered above is wrong or there are additional production mechanisms with a significant contribution.

We have also reconstructed χ_c mesons through the decay chain $\chi_c \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$ using the same data set. In the 1988-89 collider run we reconstructed 87 ± 8 χ_c 's (see Fig. 2) and we calculated the cross section for the process $p\bar{p} \rightarrow \chi_c X$ to be $\sigma(\chi_c \rightarrow J/\psi\gamma) = 3.2 \pm 0.4(\text{stat}) \begin{smallmatrix} +1.2 \\ -1.1 \end{smallmatrix} (\text{sys}) \text{ nb}$. We found that the fraction, f_χ , of J/ψ 's

coming from χ_c decays is $f_\chi = (44.9 \pm 5.5 \begin{smallmatrix} +15.4 \\ -14.1 \end{smallmatrix})\%$, but we did not have enough statistics to measure this fraction as a function of P_T . Assuming that the only processes for J/ψ production are B decays and χ_c decays, we derived the fraction f_b to be $(63 \pm 17)\%$ for $P_T^{J/\psi} > 6$

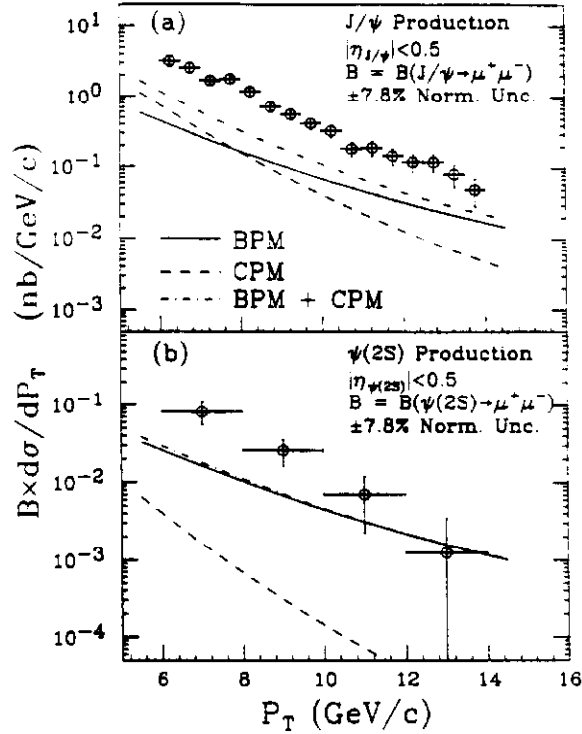


Figure 1: The product $B \times \left(\frac{d\sigma}{dP_T} \right)$ vs. P_T for (a) $J/\psi \rightarrow \mu^+ \mu^-$ and (b) $\psi(2S) \rightarrow \mu^+ \mu^-$. The circles correspond to the data. The solid curve corresponds to $J/\psi(\psi(2S))$'s produced from B meson decays. The dashed curve corresponds to $J/\psi(\psi(2S))$'s from direct charmonium production. The dot-dashed curve is their sum.

GeV/c. This value of f_b was used to obtain the b -quark production cross section from the inclusive J/ψ sample (see Fig. 7).

2.2 1992-93 data

Due to improvements in the trigger, in the 1992-93 run we have approximately a factor of 5 more J/ψ 's per pb^{-1} than in the previous run (see Fig. 3a)). In Fig. 3b) we show the J/ψ mass spectrum from a $12 pb^{-1}$ sample which represents $\sim 60\%$ of the 1992-93 data. In Fig. 4 we compare the differential J/ψ cross section from the 1988-89 data to the one from $7.5 pb^{-1}$ of 1992-93 data. In the 1992-93 run we have extended the measurement to both lower and higher P_T values. The agreement with the 1988-89 data is pretty good. In the 1992-93 data, by using the SVX we can measure the fraction of J/ψ 's from b 's directly and without any assumptions. From the measurement⁷ of the average b lifetime with inclusive J/ψ 's we have indications that the fraction of J/ψ 's coming from b 's is lower than the one we as-

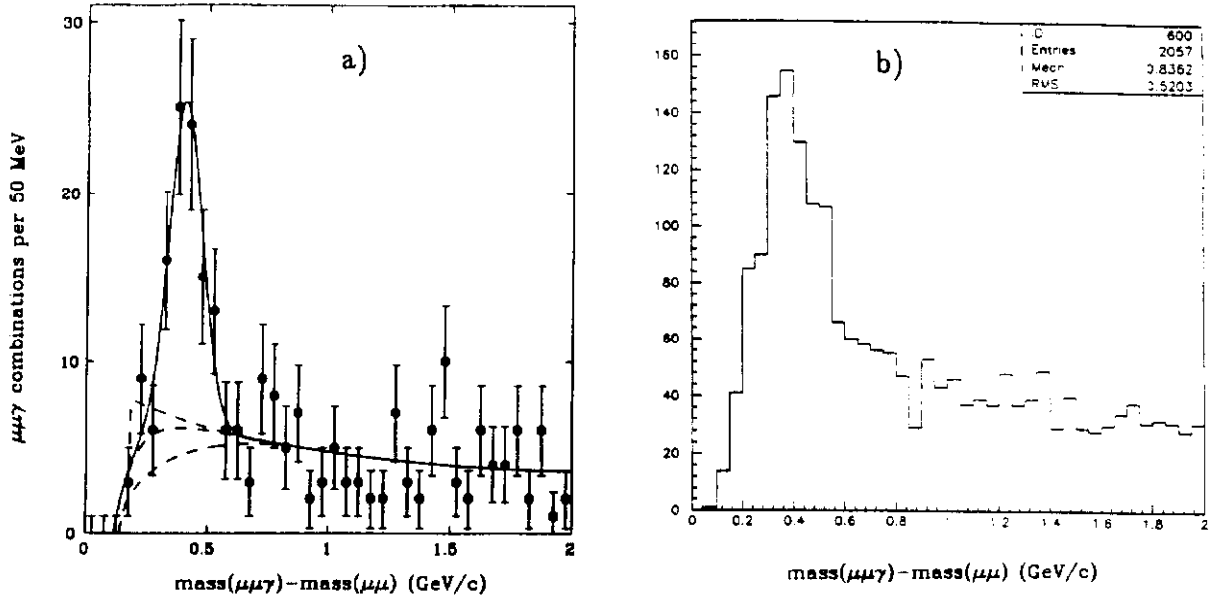


Figure 2: The mass difference ΔM for the χ_c mass region. a) 1988-89 data. The points with the error bars correspond to the data. The solid curve is a fit to a Gaussian plus the background shapes mentioned in Ref. 6. b) 1992-93 data ($\sim 12 \text{ pb}^{-1}$).

summed in the previous run. The fraction derived from the lifetime fit is 15%. Although this is the right b fraction in the lifetime sample, it should not be automatically interpreted as the fraction of J/ψ 's from b 's to be used for the b cross section measurement. The reason is that the applied track quality cuts in the lifetime analysis favor isolated muons and systematically decrease the fraction. This fraction should not be directly compared with the one we derived from the 1988-89 data either, because the fraction is a P_T dependent quantity and the P_T regions for the inclusive J/ψ sample were different in the 1988-89 and 1992-93 collider runs. The measurement of an unbiased fraction f_b from the 1992-93 run is work in progress.

A $\psi(2S)$ mass distribution reconstructed through the decay chain $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ is shown in Fig. 5 from $\sim 12 \text{ pb}^{-1}$ of the 1992-93 data. The use of the SVX in the calculation of the $\psi(2S)$ decay length indicates that the $\psi(2S)$ state has a non negligible prompt component.

With the new data set we are also reconstructing a respectable sample of χ_c decays (see Fig. 2). This sample will be used to measure the fraction f_χ and to cross check the fraction f_b measured with the SVX. Since we can now measure the J/ψ differential cross section from b 's and from χ_c 's, it will be much easier to disentangle the different

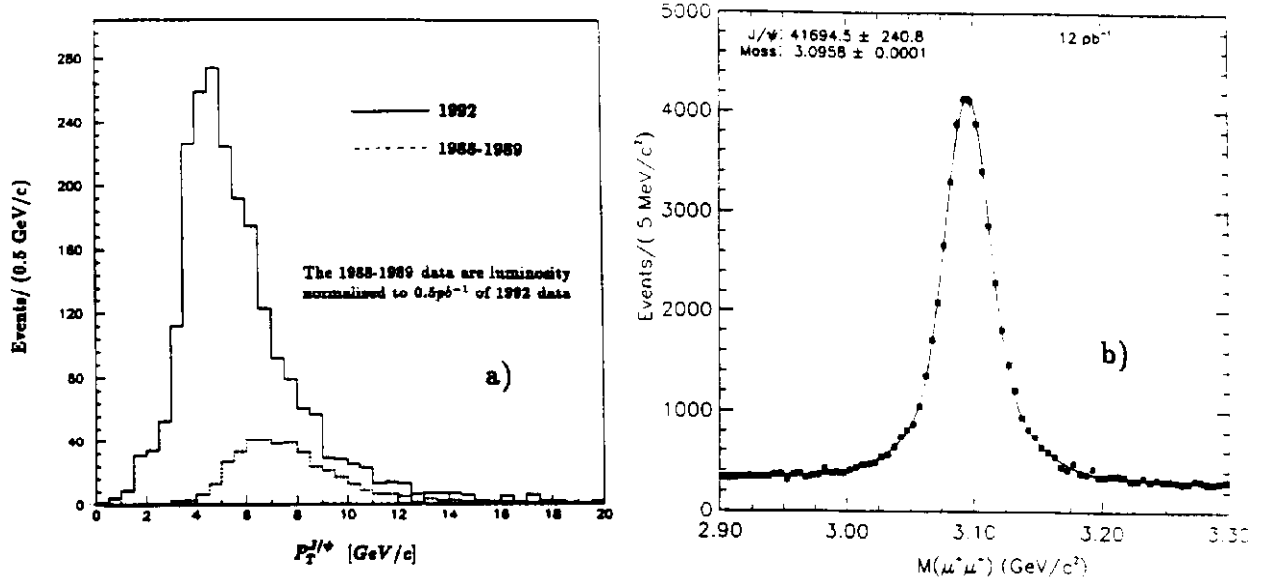


Figure 3: a) J/ψ P_T spectrum in the dimuon channel. b) J/ψ mass spectrum in the dimuon channel from 12 pb^{-1} of the 1992-93 data.

J/ψ production mechanisms. By measuring with the SVX the fraction of prompt χ_c 's we can also measure the ratio of the inclusive rates of $B \rightarrow \chi_c X$ and $B \rightarrow J/\psi X$.

Finally in Fig. 6 we show the Υ mass distribution from $\sim 12 \text{ pb}^{-1}$ of the 1992-93 data. Since Υ 's are not produced from B meson decays but they are produced either directly or from χ_c 's, we can use the measurement of $\left(\frac{d\sigma}{dP_T}\right)$ versus P_T in order to check if the direct production spectrum predicted by QCD is correct. Since $\Upsilon(3S)$ state is produced only directly, it will be especially useful for this comparison. The Υ sample offers also the possibility to check the differential production cross section at P_T values as low as $0.5 - 1.0 \text{ GeV}/c$.

3 b -quark production

3.1 1988-89 data

In Fig. 7 we show the b -quark cross sections that we derived by studying various b decay channels in the 1988-89 data. The curves in the same figure represent the theoretical predictions based on the NDE calculation. The uncertainty in the predictions arising from

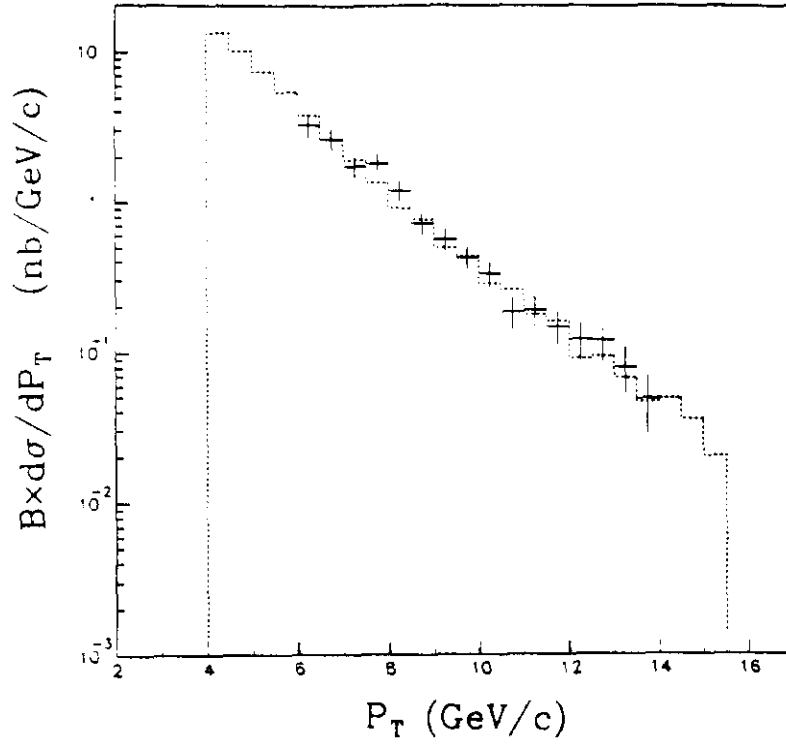


Figure 4: Comparison of the differential J/ψ cross section between the 1988-89 (points with error bars) and the 1992-93 (histogram) data for the region $|\eta_{J/\psi}| < 0.5$.

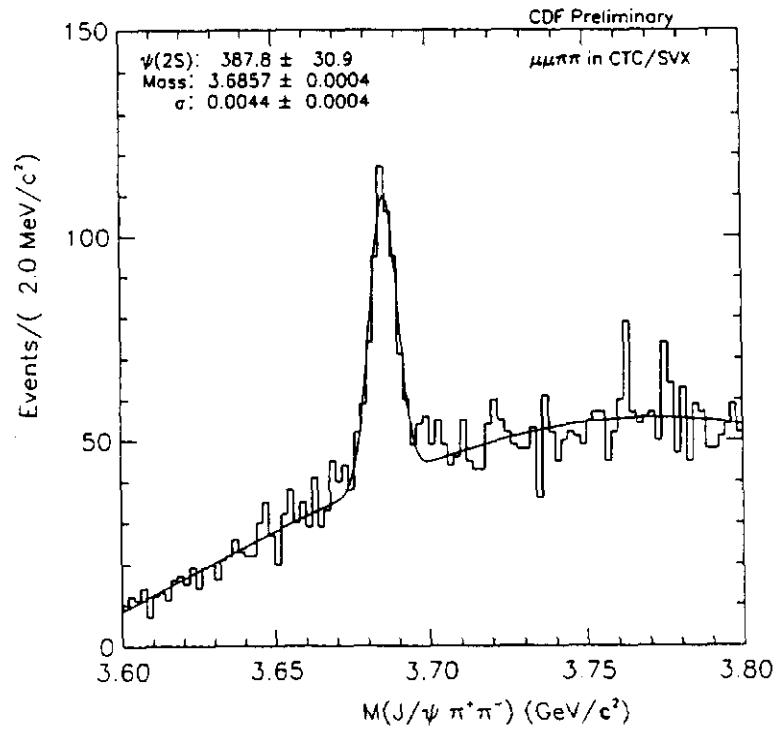


Figure 5: $\psi(2S)$ mass spectrum in the dimuon channel from $\sim 12 \text{ pb}^{-1}$ of the 1992-93 data.

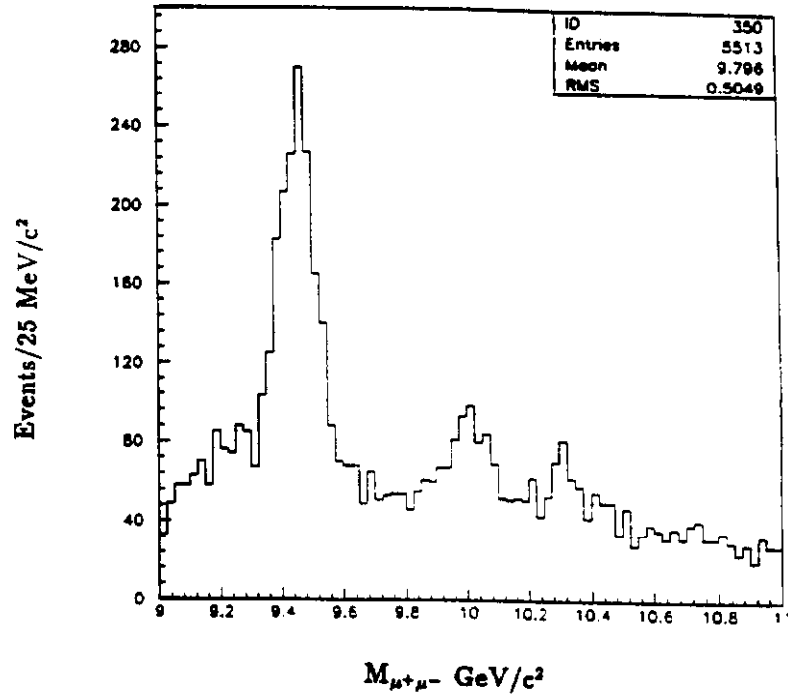


Figure 6: The dimuon mass distribution for the Υ mass region in the 1992-93 data.

choices of the renormalization scale μ , the b -quark mass and the QCD Λ parameter are also shown. The dashed lines correspond to the central value and the upper and lower allowed predictions by using the DFLM structure functions. The dotted lines correspond to similar predictions by using the MT structure functions. Finally the solid lines represent the central value and the upper allowed prediction by using the MRSD0 structure functions. The b -quark production cross section from the inclusive $J/\psi(\psi(2S)) \rightarrow \mu^+\mu^-$ channels was based on the measurement of the integrated $J/\psi(\psi(2S))$ cross section for $P_T > 6$ GeV/c (see section 2.1) and on the fraction f_b of $J/\psi(\psi(2S))$'s coming from b 's. For the J/ψ 's we used the fraction discussed in section 2.1. For the $\psi(2S)$'s we assumed that they all originate from B decays⁸.

The b -quark cross section from the $e\mu$ sample shown in Fig. 7, is a single- b inclusive cross section based on the observation of a correlated lepton pair that originates from the $b\bar{b}$ produced in the event. This measurement has been based on ~ 1000 lepton pairs. It is interesting that although this cross section is measured at a similar P_T^b as the cross section from inclusive J/ψ 's and $\psi(2S)$'s it has a lower central value. This is an indication that there might be something wrong with the assumptions we made to derive f_b from the inclusive J/ψ and $\psi(2S)$ channels.

The B meson production cross sections from the exclusive de-

cay channels $B^\pm \rightarrow J/\psi K^\pm$ and $B^0 \rightarrow J/\psi K^{0*}$ were based on 14.1 ± 4.3 and 9.6 ± 4.6 events respectively and therefore they were statistically limited. The corresponding b -quark cross sections are also shown in Fig. 7.

From the inclusive electron production rate and the associated electron- D^0 production rate we derived the b -quark cross section for four different ranges of P_T^b ; from the inclusive muon production rate in the same data we derived the b -quark cross section for two different ranges of P_T^b . The major systematic uncertainty in these inclusive lepton measurements was the level of the knowledge of the background. This is greatly improved in the 1992-93 run due to the upgrades of the detector.

From the comparison of the data with the theoretical predictions in Fig. 7 we observe that the experimental b cross section is larger than the theoretical one at the Tevatron energy. There is a clear excess in the observed rate at small P_T^b . At larger values of P_T^b , the data are consistent with the upper extreme of the theoretical band. The measurements of b -quark production cross sections from the UA1 experiment in $p\bar{p}$ collisions at $\sqrt{s} = 630 \text{ GeV}$ agree much better with the theoretical predictions than the CDF measurements at $\sqrt{s} = 1.8 \text{ TeV}$ do⁹. There have been several attempts to explain the difference such as consideration of higher order corrections to the next-to-leading order theoretical calculation, higher order small- x corrections to the partonic cross sections and modification of the gluon densities¹⁰.

We know that several of the 1988-89 CDF b -quark cross section measurements were statistically limited or were derived under certain assumptions; we expect that the analysis of the data set we collected during the 1992-93 run will shed light onto the problem.

3.2 1992-93 data

Since we know that the measured fraction f_b for both J/ψ 's and $\psi(2S)$'s is smaller than the one we assumed in the 1988-89 analyses (see section 2.2), we expect that the b cross sections based on the inclusive quarkonia samples will become more consistent with the theory.

From $(14.3 \pm 1.0) \text{ pb}^{-1}$ of the 1992-93 data we also reconstructed $104 \pm 21 \text{ } J/\psi K^\pm$ and $26 \pm 8 \text{ } J/\psi K^{0*}$ events for $P_T^B > 6.0 \text{ GeV}/c$ and $P_T^B > 9.0 \text{ GeV}/c$ respectively. The corresponding b -quark cross sections are shown in Fig. 8. The errors are statistical and systematic combined in quadrature. These new measurements, although statistically consistent with the corresponding ones of the 1988-89 data, they are closer to the theoretical predictions. Since there are sufficient statistics in the $B^\pm \rightarrow J/\psi K^\pm$ decay channel, this channel has been also used to measure the differential B meson cross section. The measurement

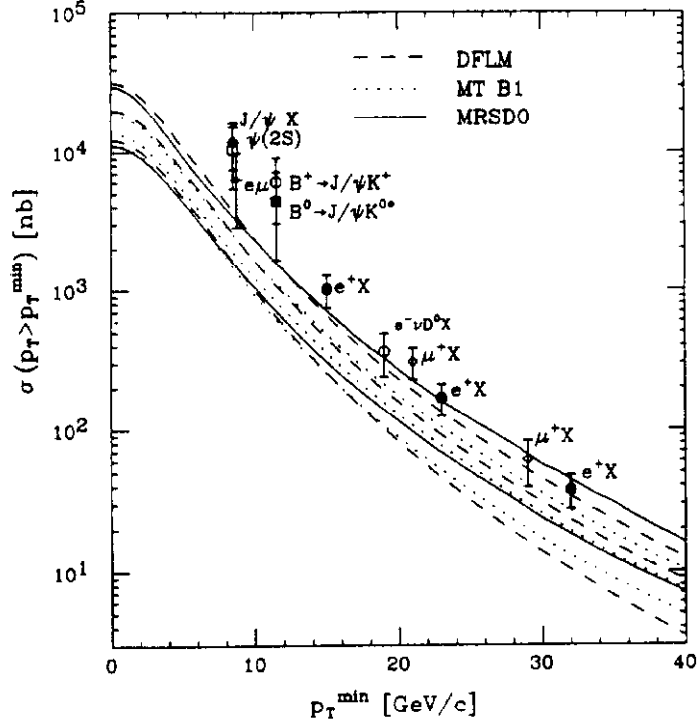


Figure 7: Integrated b P_T distribution at 1.8 TeV: 1988-89 CDF data versus NLO QCD.

suggests that the shape of the theoretical cross section differs from the experimental result since there is an excess in the observed rate at low P_T^B (see Ref. 11).

Finally we have derived the b -quark cross section for two different ranges of P_T^b from the associated muon- D^0 production rate. These two measurements are based on 8.8 and 4.4 pb^{-1} of 1992-93 data respectively, and they will certainly improve when we use the full data set.

4 Summary

During the 1988-89 collider run CDF has shown that one can study quarkonia physics and b physics even in a harsh $p\bar{p}$ collider environment. The 21 pb^{-1} we collected with the upgraded CDF detector during the 1992-93 run, are leading us to a rich program which focuses on the production and decay of quarkonia and b -quarks, and which will answer many of the questions posed during the 1988-89 collider run.

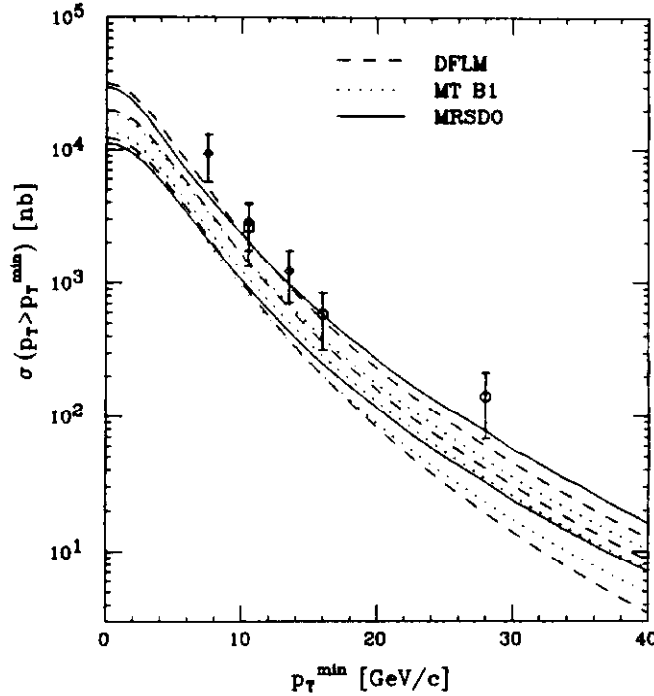


Figure 8: Integrated b P_T distribution at 1.8 TeV: 1992-93 CDF data versus NLO QCD. The diamonds correspond to the decay $B^\pm \rightarrow J/\psi K^\pm$, the square to $B^0 \rightarrow J/\psi K^{0*}$ and the circles to $B \rightarrow \mu D^0 \nu X$.

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